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Energy from Vascular Plant Wastewater Treatment Systems[1]

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Water hyacinth (Eichhornia crassipes), *duckweed* (Spirodela *sp. and* Lemna *sp.*), *water pennywort* (Hydrocotyle ranunculoides), *and kudzu* (Pueraria lobata) *were anaerobically fermented using an anaerobic filter technique that reduced the total digestion time from 90 d to an average of 23 d and produced 0.14–0.22 m³ CH_4/kg (dry weight) (2.3–3.6 ft³/lb) from mature filters for the 3 aquatic species. Kudzu required an average digestion time of 33 d and produced an average of 0.21 m³ CH_4/kg (dry weight) (3.4 ft³/lb). The anaerobic filter provided a large surface area for the anaerobic bacteria to establish and maintain an optimal balance of facultative, acid-forming, and methane-producing bacteria. Consequently the efficiency of the process was greatly improved over prior batch fermentations.*

Cultivation of higher plants for the specific purpose of fuel production is not economically feasible at present (Benemann, 1978). However, cultivation of higher plants for use in wastewater treatment, and incorporation of these plants into a system where the biomass is harvested for fuel production is economically appealing at the present time. Since this biomass is a by-product of wastewater treatment, it has a positive environmental impact, and thus poses no threat as a competitor to food, feed, or fiber-producing plants.

The National Aeronautics and Space Administration (NASA) has developed and is operating vascular aquatic plant wastewater treatment systems for both domestic and chemical wastes at the National Space Technology Laboratories (NSTL) (Wolverton and McKown, 1976; Wolverton and McDonald, 1977, 1979a, b, c). As a part of this program and Life Sciences study, NASA has investigated a variety of plants which have at least one common characteristic, i.e., a high potential productivity when cultivated and harvested to achieve optimal growth conditions. During the past 5 yr that these systems have been in operation, NASA has been continuously searching for the most productive means of using the harvested plant biomass. One such method of using the biomass by-product from aquatic plant wastewater treatment systems is the conversion of the plant material into methane through anaerobic digestion. The energy produced from biomass digestion can be used for aeration and other wastewater treatment energy requirements as well as other energy-consuming needs such as heating, cooking, and hot water. The residual sludge from the digesters can also be used for fertilizer, feed products, etc.

The conversion of waste material, particularly animal manure, has been studied for many years. The microbial degradation processes involved in anaerobic digestion can be found in studies by Boswell (1947), Ghosh and Klass (1976), and

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Ghosh and Pohland (1974). Two-phase digestion systems to provide optimal conditions for the acid-forming and methane-producing microorganisms were researched by Pohland and Ghosh (1971) in an effort to reduce the overall digestion time. The highlights of the critical parameters to be noted and controlled have been organized by the National Academy of Sciences (1977), Johnson (1977), and Singh (1971) into handbooks for the general public.

NASA's original studies on the bioconversion of water hyacinth (*Eichhornia crassipes*) into methane in 1975 consisted of simple batch fermentations requiring long digestion periods of 90–120 d (Wolverton et al., 1975). In an effort to minimize the digestion time, recent studies have focused on 2-phase digestion chambers using the anaerobic filter concept first demonstrated by Young and McCarty (1969) for reducing the biochemical oxygen demand (BOD) of wastewater. Improvement of the anaerobic filter technique for the rapid removal of low concentrations of BOD in wastewater has been made by Genung et al. (1979), Koon et al. (1979) and Switzenbaum and Jewell (1978).

In the following experiments, the 2-phase digester system consisted of a first chamber containing the pulp (fiber), water, and plant juices from the blending process and a second chamber, the "anaerobic filter," consisting of a vessel packed with inert pea gravel which provides an extensive surface area for receiving only liquids from the fiber-containing chamber. The second chamber for the anaerobic filter also serves as an isolation chamber for anaerobic bacteria when the first chamber is emptied and restocked.

Water hyacinth (*Eichhornia crassipes*), duckweed (*Spirodela* sp. and *Lemna* sp.) and water pennywort (*Hydrocotyle ranunculoides*) were the aquatic plants used in the study. The highly prolific terrestrial plant *Pueraria lobata*, commonly referred to as kudzu, was also studied. The kudzu vine is a terrestrial plant which covers thousands of acres in southern and central states of the United States. Kudzu possesses several characteristics which make it an ideal candidate for energy farms. It reproduces rapidly by either vegetative means or seeds. It is an aggressive plant as evidenced by its resistance to eradication. Since the kudzu vine is a legume, it can thrive in poor soil that is useless for agriculture and actually improves the land by restoring nitrogen to the soil. Due to its long roots, kudzu can also withstand droughts. Definitive growth rates on the kudzu vine are not available. NASA at NSTL has noted that a kudzu vine can produce 1–1.5 ft of new vine each day with an average mass of 3.7 g (dry weight)/d (Wolverton, 1980).

MATERIALS AND METHODS

Water hyacinth, duckweed and water pennywort used in these experiments were grown on sewage lagoons located at the National Space Technology Laboratories. Kudzu vines were collected from fields near NSTL for experiment #8 and from experimental growth study sites on NSTL for #'s 9 and 10. The whole plants for the aquatic species and only the aerial portion for the terrestrial species were blended into a slurry with approximately 1 ml of tap water per g wet plant and placed into an 8-l glass vessel. This vessel contained small pea gravel, 9 cm deep, in the bottom. The 8-l vessel was connected to a 730-ml glass vessel (anaerobic filter) which was filled with small pea gravel (Fig. 1). Fifty ml of bacterial

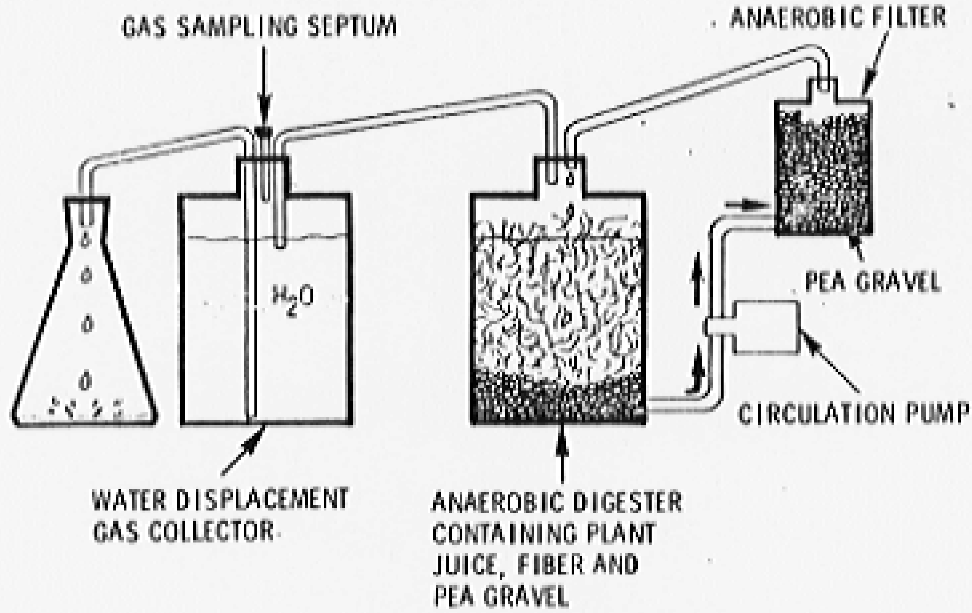

Fig. 1. Two-stage anaerobic digester system for producing methane.

seed solution from an on-going anaerobic digester was added to the initial start-up batch. Liquid from the 8-l vessel was pumped through the anaerobic filter and recycled through the large vessel continuously 8 hr per day. The anaerobic filter was kept sealed as new batches of plant material were added to the digester. The digestion temperature was maintained at 37° ± 1°C using an incubator. Gas samples were taken through the rubber septum and analyzed with a Fisher-Hamilton Gas Partitioner Model 29. The total volume of gas produced was measured as the volume of water displaced. The initial plant samples were analyzed by Raltech Scientific Services. Plants used in subsequent experiments were collected from the same growth areas with the exception of kudzu.

The solids content of the fresh biomass was determined by drying appropriate plant samples to a constant weight at 100°C in a forced air oven. The solids content of the plants were as follows: water hyacinth, 5.0%; water pennywort, 5.1%; duckweed, 4.8%; kudzu near NSTL, 20.0%; and kudzu on NSTL, 16.0%. The difference in the solids content of the kudzu vines was probably due to the age of the vines. The vines collected from neighboring fields were longer and older than those collected on NSTL.

RESULTS AND DISCUSSION

Nine experiments were conducted to determine the digestion times and the total volume of methane that can be obtained from water hyacinth, water pennywort, kudzu and a combination of duckweed/water hyacinth using the anaerobic filter technique. The age of the anaerobic filter was also noted in order to observe improvements in the efficiency of the methane production rates as a function of the anaerobic filter age.

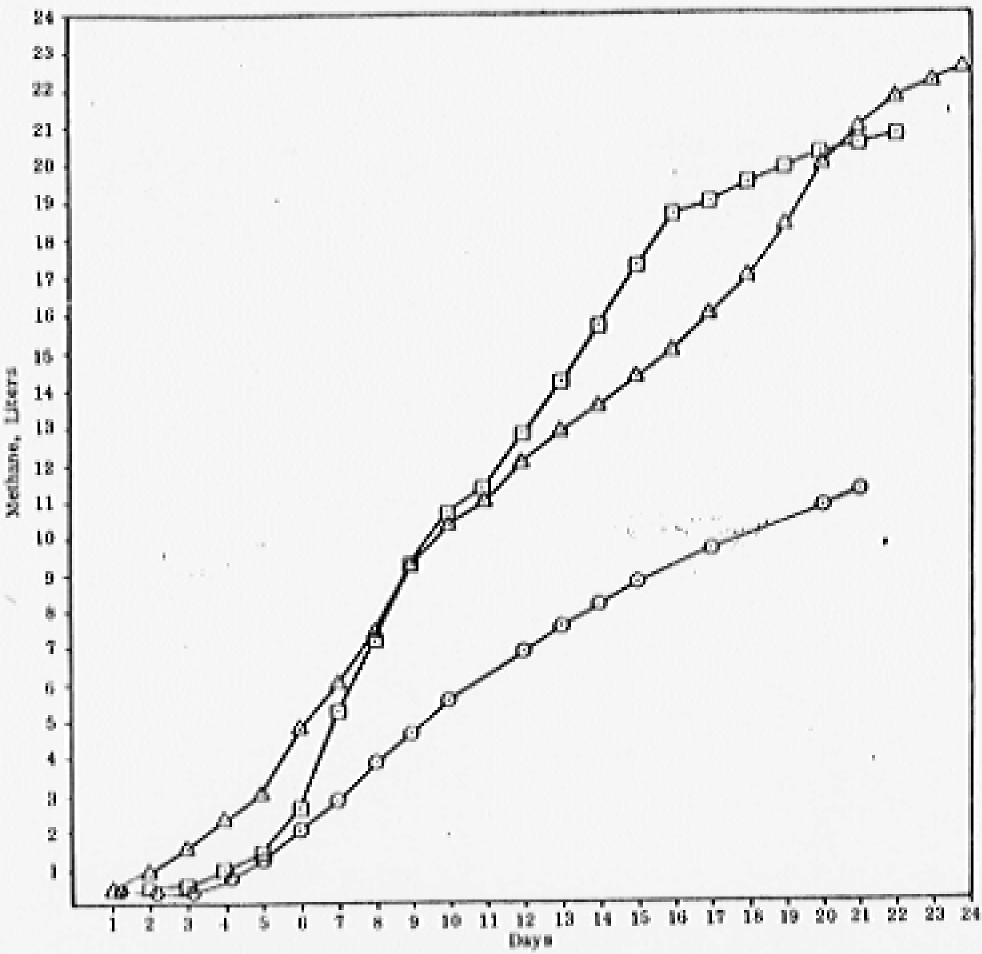

Fig. 2. Comparison of water hyacinth digestion rates and anaerobic filter age. Legend: ⊙ = 3.00 kg water hyacinth, new anaerobic filter; △ = 2.97 kg water hyacinth, 22-day old filter; ⊡ = 2.00 kg water hyacinth, 46-day old filter.

The rates of methane production for experiments 1–5 have been graphically compared in Fig. 2 and 3. Fig. 2 and 3 show a definite improvement in reducing the lag time between initiating anaerobic digestion and producing methane once the anaerobic filter has been matured through at least one digestion cycle. As shown in Fig. 2 for experiments 1–3, there was further improvement in the performance of the anaerobic filter during the third digestion cycle, thus indicating that the microbial balance in the anaerobic filter of the facultative, acid-forming, and methane-producing bacteria is still changing in order to achieve an optimal balance. After the anaerobic filter portion of the system has been sealed and matured, the filter should never be reopened or replaced unless by accident the bacterial balance is irreversibly upset. The anaerobic filter serves as a separate anaerobic bacterial reservoir which has minimal oxygen contact even when the primary solids chamber is emptied and refilled. The use of a separate vessel for

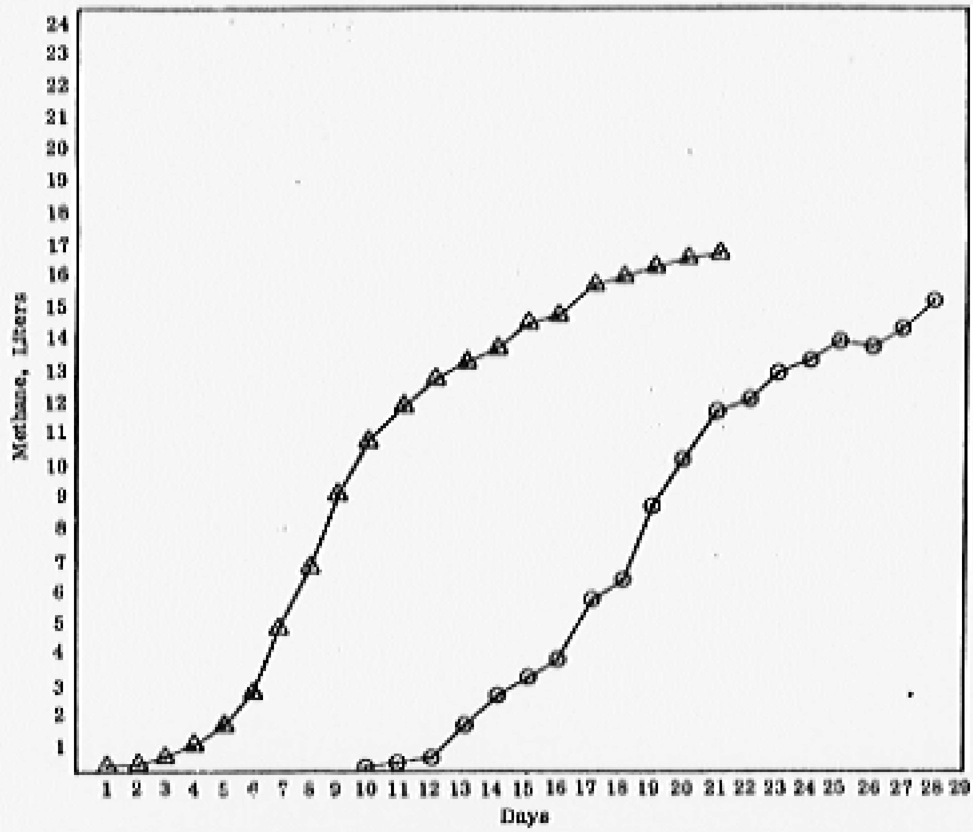

Fig. 3. Comparison of water pennywort digestion rates and anaerobic filter age. Legend: ⊙ = 2.00 kg water pennywort, new filter; △ = 2.15 kg water pennywort, 43-day old filter.

a filter assures sustaining a rich, undisturbed anaerobic bacterial culture for inoculating subsequent digestions.

The raw data for the total biogas and methane production is given in Table 1. The digestion time varied from 21–28 d for the aquatic species with an average of 23 d. For the terrestrial species, the digestion time varied from 31–35 d with an average of 33 d. The digestion time has been dramatically reduced by approximately 75% from the previous batch digestions. Therefore, the size of the digestion chambers can be reduced accordingly in order to generate the same volume of biogas and methane.

The calculated results are shown in Table 2. The maximum volume of methane produced for water hyacinth and water pennywort in this study was 0.198 m^3/kg (3.17 ft^3/lb) and 0.146 m^3/kg (2.34 ft^3/lb), respectively. Since the initial anaerobic filter age was approximately the same, results indicate that water hyacinth is easier to digest anaerobically than water pennywort. This observation is further substantiated by the data presented in Table 3. Water hyacinth has approximately twice as much hemicellulose content as the water pennywort. Hemicellulose is a substance found in plant tissue that is more complex than a sugar but less

TABLE 1. FINAL RESULTS FOR EXPERIMENTS 1–8 (GAS VOLUMES AS MEASURED AT 37°C).

Exp. #	Species	Wet weight, kg	Dry weight, kg	Total biogas, liter	Total methane, liter	Initial filter age, days	Digestion time, days
1	water hyacinth	3.00	0.150	35.3	11.1	0	21
2	water hyacinth	2.97	0.149	43.3	22.5	22	24
3	water hyacinth	2.00	0.100	37.5	20.8	46	22
4	water pennywort	2.07	0.105	33.1	15.1	0	28
5	water pennywort	2.15	0.108	28.7	16.6	43	21
6	50:50 water hyacinth/duckweed	2.00	0.098	40.1	22.6	164	21
7	kudzu[a]	1.02	0.204	67.4	34.3	226	34
8	kudzu[b]	1.14	0.182	81.0	44.5	>250	31
9	kudzu[b]	1.29	0.207	90.6	49.1	>250	35

[a]Collected from fields in Hancock Co., MS near NSTL.

[b]Collected on NSTL.

TABLE 2. CALCULATED RESULTS OF EXPERIMENTS 1–8 (ALL GASS VOLUMES CORRECTED TO 20°C).

Exp. #	Total biogas		% CH_4	Total methane[a]	
	m^3/kg	ft^3/lb		m^3/kg	ft^3/lb
1	0.222	3.56	31.6	0.070	1.13
2	0.276	4.43	52.0	0.143	2.30
3	0.356	5.71	55.5	0.198	3.17
4	0.299	4.80	45.6	0.137	2.19
5	0.253	4.05	57.8	0.146	2.34
6	0.389	6.30	56.4	0.219	3.55
7	0.314	5.08	50.8	0.160	2.59
8	0.423	6.85	54.9	0.232	3.76
9	0.438	6.74	54.2	0.237	3.70

[a]Dry weight basis

TABLE 3. CELLULOSE, HEMICELLULOSE, AND LIGNIN ANALYSES.

Species	% Dry weight		
	Cellulose	Hemicellulose	Lignin
Water hyacinth	21.5	33.9	6.01
Water pennywort	15.7	15.1	7.28
Duckweed	10.0	21.7	2.72
Kudzu[a]	26.2	20.8	10.5

[a] Collected from fields in Hancock Co., MS near NSTL

complex than cellulose. Therefore, the hemicellulose is generally considered more amenable to bacterial degradation than cellulose. The lignin contents in the water hyacinth and water pennywort did not differ significantly. In fact the lignin contents of all 4 used in this study were low. In anaerobic digestion processes, lignin is considered to be a nonbiodegradable substance which reduces the availability of the cellulose to bacterial attack.

A water hyacinth/duckweed mixture was digested and the results of 0.219 m^3 CH_4/kg (3.55 ft^3/lb) were not significantly different from the maximum methane production obtained with water hyacinth alone. This mixture was selected because water hyacinth and duckweed are often together in aquacultural wastewater treatment facilities with water hyacinth dominant in the summer and duckweed in the winter (McDonald and Wolverton, 1980; Wolverton and McDonald, 1979b).

Since mature filters were used with all kudzu digestions, only the raw data are presented in Table 2. Lower methane production was obtained in experiment 7 than with experiments 8 and 9. The average methane production from the 2 latter experiments with kudzu was 0.234 m^3/kg (3.73 ft^3/lb) as opposed to only 0.160

TABLE 4. PROXIMATE COMPOSITION.

Species	% Dry weight				
	Crude protein	Fat	Fiber	Ash	Total carbohydrate[a]
Water hyacinth	14.7	1.59	18.6	11.1	54.0
Water pennywort	23.4	2.10	11.8	17.4	45.2
Duckweed	37.0	3.40	15.6	12.5	31.5
Kudzu[b]	16.3	2.11	31.3	8.2	42.1

[a] Total carbohydrate = 100-(crude protein + fat + fiber + ash)

[b] Collected from fields in Hancock Co., MS near NSTL

TABLE 5. MISCELLANEOUS ELEMENTAL ANALYSES.

Species	% Dry weight				
	Nitrogen	Phosphorus	Potassium	Carbon	C:N
Water hyacinth	2.35	0.445	1.99	39.9	17.1
Water pennywort	3.75	0.606	2.80	37.0	10.1
Duckweed	5.92	0.955	2.91	43.7	7.1
Kudzu[a]	2.61	0.222	1.83	43.1	17.1

[a]Collected from fields in Hancock Co., MS near NSTL.

m^3/kg (2.59 ft^3/lb) for experiment 7. The kudzu vines used in experiment 7 were longer and older than those in 8 and 9. Vines from the fields near NSTL were transplanted to experimental growth sites on NSTL and harvested on a monthly basis. Therefore, the difference in methane production was not due to a difference in plant species. Longer digestion times were required with kudzu than the aquatic species. This was probably due to the higher fiber content of kudzu (31.3%) as compared to an average content of 15.3% for the 3 aquatic species. The lignin content of kudzu was also slightly higher than the 3 aquatics.

Table 4 shows the gross or proximate composition of the plants prior to anaerobic digestion. Duckweed had the highest crude protein content, 37% of dry weight. Kudzu had the highest fiber and the lowest ash content. Table 5 gives the nitrogen, phosphorus, and potassium contents of the species on a dry weight basis. These elements are the most common ones noted in order to judge fertilizer value. During anaerobic digestion, some nitrogen is generally lost. The extent of denitrification is dependent on the method and care of the anaerobic digestion and also on the initial C:N ratio. The C:N ratios of the species used in this study are given in Table 5. In general, the lower the ratio, the higher the nitrogen loss due to a surplus of nitrogen. However, all minerals such as potassium and phosphorus will remain in the sludge. In fact, these minerals will be more concentrated due to a reduction in the initial solids content from loss of nitrogen and carbon in the forms of ammonia, nitrogen gas, methane, and carbon dioxide during the anaerobic digestion. A small amount of sulfur will also be lost in the form of hydrogen sulfide. Plant composition will vary from site to site; however, the 3 aquatic species were harvested from the same areas for subsequent experiments. The kudzu composition may have been slightly different between the vines used in experiment 7 and those used in experiments 8 and 9. However, any differences, which were due more to the vine age than to the collection site, would probably have been slightly higher cellulose and lignin contents in the older vines.

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